

Measurement and Modeling of Rollover Airborne Trajectories

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ABSTRACT

Much has been written about reconstruction techniques and testing methods concerning vehicle rollovers. To date, most of the literature describes rollovers as one-dimensional events. Rollovers account for a disproportionate fraction of serious injuries and fatalities among all motor vehicle accidents. The three-dimensional nature of rollover sequences in which a rolling vehicle experiences multiple ground contacts contributes to the environment where such injuries occur.

An analytical technique is developed to model the airborne segments of a rollover sequence as a parabolic path of the vehicle center of gravity. A formulation for the center of gravity descent from maximum elevation to full ground contact is developed. This formulation contains variables that may be readily determined from a thorough reconstruction. Ultimately, this formulation will also provide a vertical ground impact velocity at contact.

Measurements of airborne segments from two high-speed rollover events – a dolly rollover test and a real-world rollover crash - are presented as a basis to evaluate the model. The ability to theoretically model

two-dimensional trajectory paths is demonstrated and the concept of an *effectively* airborne rollover segment is presented. Comparisons between vehicle descent predicted by the model and from the rollover tests are presented.

The measured values of descent distance from the rollover tests generally slightly exceed the predicted values. It is shown that accuracy may be improved by careful selection of drag factors based on non-uniform over-the-ground deceleration observed in on-road and soft surface vehicle rollover events. The application of the trajectory model to obtain vertical vehicle motion in real-world rollover crashes involves reconstruction based on the topography of the rollover path and physical evidence related to ground contacts.

INTRODUCTION

Vehicle rollovers comprise less than 5% of all tow-away motor vehicle accidents in the United States [1], most of which involve off-road ground contacts. The disproportionate occurrence of serious or fatal injuries to occupants in rollovers has prompted studies by industry and government regulatory entities attempting to define strategies that will mitigate the problem [1]. A characterization of the environment in a rolling vehicle to which an occupant is exposed is assisted by detailed understanding of the dynamics of the rollover. The dynamics, or rollover mechanics, include characterization of translational and vertical ground impact speeds, deceleration, and angular velocity of a rolling vehicle.

A rollover reconstruction may be useful in explaining damage patterns to a vehicle, such as roof panel or support pillar residual deformation. Estimates of the magnitude of ground contact forces require an approximation of the velocity of the center of gravity (CG) when the periphery of the vehicle contacts the terrain. Vehicle ground contact velocity can be substantially resolved into components perpendicular and parallel to the local contact plane. The vertical component of the CG velocity at ground impact strongly influences the severity of contact forces experienced by a rolling vehicle. Trajectory mechanics can be utilized to determine this speed, and, in conjunction with roll, pitch and yaw rates, speed estimates at the periphery of the vehicle at impact. When a rolling vehicle strikes the ground, the vertical component of the velocity of the CG diminishes or becomes zero. The change in magnitude of the vertical velocity of the CG during a ground impact is key in characterizing the vertical deceleration of the vehicle and approximating the vertical component of forces applied through the area of impact at the vehicle periphery. Roll, pitch and yaw angles, while influential in establishing the elevation of the CG of a vehicle at the beginning and end of an airborne trajectory, do not directly affect the trajectory mechanics computations, and are not detailed in this study.

An approach to determine the two-dimensional trajectory mechanics of a rolling vehicle is presented. The analyses presented here focus on the vertical component of ground contact velocity due to the elevation change alone of the CG of a rolling vehicle. Two high-speed rollover events – a dolly test and a real-world crash of passenger vehicles – were analyzed to evaluate the trajectory modeling.

OBJECTIVES

The objectives of this study are summarized as follows:

- 1) Present center of gravity elevation results from a high-speed real-world rollover and a high-speed dolly rollover test.
- 2) Develop two-dimensional kinematic relationships to model the airborne trajectories of a rolling vehicle.
- 3) Determine the applicability of the model using airborne trajectories obtained from well-documented rollovers.
- 4) Compare rollover vehicle trajectory results with analytical predictions.
- 5) Describe the application of the model in reconstruction of rollover events.

TECHNICAL APPROACH

The motion of a rolling vehicle can be characterized as a series of potentially injurious and damaging ground contacts separated by airborne intervals as the vehicle continuously rotates about the roll axis with some angular displacement about the yaw and pitch axes until rest.

A ground contact that significantly influences the path of the CG is a finite process that comprises initial contact followed by some elastic and often plastic deformation of the vehicle and roll surface, during which the CG decelerates perpendicular and parallel to the contact surface. As the process concludes, the vehicle and roll surface restore to a statically deformed state. The CG path during a significant ground contact generally exhibits a relative minimum elevation. This is a result of vertical deceleration of the vehicle corresponding to the maximum vertical impact force that may exceed that which is parallel to the contact surface.

ROLLOVER TRAJECTORY MECHANICS THEORY

The translational deceleration of the CG of a rolling vehicle is the basis for many roll mechanics computations, including speed, rollover rate and trajectory analysis estimates [2,3,4], and can be obtained from

$$v_i^2 - v_f^2 = 2 \int a dx \quad (1)$$

This is the familiar, widely used one-dimensional relationship between speed, distance and acceleration for a point mass. For a rolling vehicle, a represents the average deceleration along the roll path, and is often referred to as a drag factor. With this formulation, the drag factor must include the effect of elevation changes of the terrain [2,3,4,5]. Eqn. (1) may be applied for discrete segments of a roll sequence to estimate intermediate speeds at the beginning and end of an interval, such as shown in the hypothetical velocity-time diagram for a rolling vehicle in Figure 1, or to estimate the speed of the vehicle at overturn. The integral in Eqn. (1) is evaluated by selecting a representative average drag factor, over the interval distance, $x_f - x_i$.

The average drag factor for a rolling vehicle can be expressed, with rotational and potential energy assumed negligible, as:

$$\bar{a} = \frac{v_i - v_f}{\Delta t} \quad (2)$$

Though a rolling vehicle decelerates due to discrete ground contacts, Eqns. (1) and (2) provide a simplified model of translational speed as a function of average drag factor. Figure 1 shows over-the-ground (OTG) velocity for a hypothetical vehicle rollover on a level surface showing four significant ground contacts and three airborne segments, with average deceleration a , obtained from Eqn. (1) or (2). Each airborne segment, represented by horizontal segments on the diagram, begins and ends during significant ground contacts. During airborne segments, CG vertical deceleration and acceleration occur due to gravitational forces, essentially no translational deceleration occurs, and the trajectory of the CG is subject to analysis using two-dimensional kinematic theory.

The four, sloped segments represent ground impacts during which translational deceleration may occur due to friction or plastic and elastic deformation forces, and vertical deceleration and acceleration may occur due to plastic and elastic deformation forces.

Application of the trajectory model is simplified by treating the contact process as an instantaneous impulse at the relative minimum elevation. It is assumed that all translational deceleration, perpendicular to gravity, occurs during these impulses, and that it is

reasonably modeled by Eqns. (1) or (2). The trajectory mechanics approach described below contemplates airborne segments, such as from positions 1 to 2, and 2 to 3, in Figure 1, separated by an infinitesimal time interval in which the vertical velocity of the CG is zero.

Figure 2 depicts a segment of time duration t_s with a parabolic trajectory of the CG starting at x_i at an elevation z_i , peaking at x_a at elevation $z_{cg,max}$ and concluding at x_f at elevation z_f . The duration of the trajectory, t_s , is the sum of time from initial position to maximum ascent t_a , and the time from maximum ascent to the ground impact, t_d . The time interval over which an airborne vehicle traverses a segment can often be estimated from physical evidence and corresponding translational speed calculations using Eqn. (2).

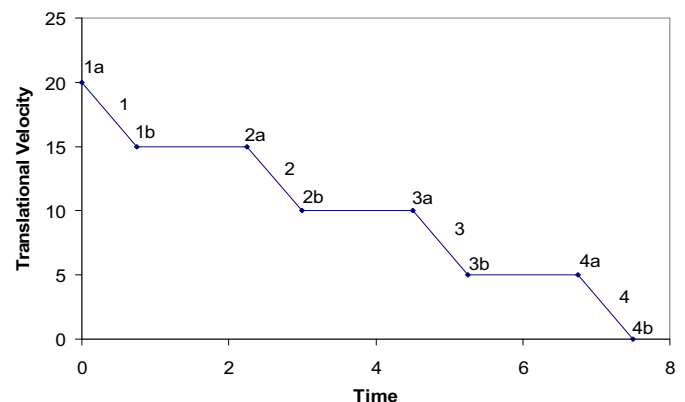


Figure 1. OTG velocity-time diagram for hypothetical rollover.

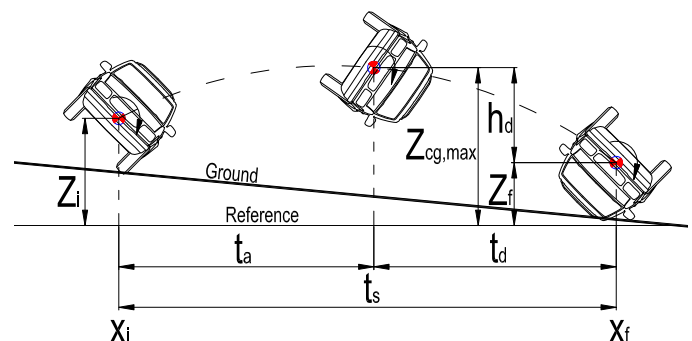


Figure 2. Generalized airborne rollover segment with key nomenclature.

The parabolic trajectory of the CG during an airborne segment can be modeled in terms of horizontal distance, x , initial and final positions, x_i and x_f , initial and final elevations of the CG, z_i and z_f , and peak CG elevation, $z_{cg,max}$ (z_{max}), shown in Fig. 2, as:

$$z = 2(z_{max} - z_i) \left(I + \sqrt{\frac{z_{max} - z_f}{z_{max} - z_i}} \right) \left(\frac{x - x_i}{x_f - x_i} \right)^2 + (z_i - z_f) \left(\frac{x - x_i}{x_f - x_i} \right) + 2(z_{max} - z_i) \left(I + \sqrt{\frac{z_{max} - z_f}{z_{max} - z_i}} \right) \left(\frac{x - x_i}{x_f - x_i} \right) + (z_{max} - z_i) \quad (3)$$

z_i and z_f can be determined from the vehicle orientation at each impact. Since horizontal speed, v_x , is essentially constant for an airborne segment, the trajectory may also be expressed in terms of speed and segment duration, t_s . The vertical component of vehicle ground contact velocity can be obtained from the trajectory model. Since the vertical velocity is zero at maximum CG elevation (x_a, z_{max}), the vertical component of ground contact velocity at the end of the interval is given by

$$v_z = \sqrt{2gh_d} \quad (4)$$

where h_d is the vertical descent from peak elevation, z_{max} , to ground contact. The descent height, h_d , may be expressed in terms of t_s , z_i and z_f , obtained from reconstruction analyses, as

$$h_d = \frac{1}{2} g \left(\frac{t_s}{2} - \frac{z_f - z_i}{gt_s} \right)^2 \quad (5)$$

From Eqn. (4), the vertical component of ground contact velocity is then

$$v_z = g \left(\frac{t_s}{2} - \frac{z_f - z_i}{gt_s} \right) \quad (6)$$

The derivation of these trajectory relationships is given in Appendix A.

Segments of rollover sequences during which the vehicle achieves some elevation could include ground contacts that may not significantly influence the path of the CG, such as certain contacts by the front or rear of the vehicle, or with tires and wheels extended by suspension springs. If the path represented by, for

example, positions 2-3 in Figure 1, can be reasonably well modeled by Eqn. (3), the motion will be considered *effectively* airborne (see Figure 6), and the vertical component of ground contact velocity may be approximated by Eqn. (6).

Reconstruction of a segment of a rollover sequence based on physical evidence, analysis and terrain topography is usually necessary to identify trajectories that are *effectively* airborne. When evidence of vehicle ground contacts at rollover sites is identified, such as from impacts of sufficient magnitude to fracture or deform vehicle components, or to imprint the contact surface, vehicle roll positions can be reconstructed with reasonable accuracy, and *effectively* airborne segments may be determined.

METHOD FOR TRAJECTORY THEORY EVALUATION

The approach to evaluate the trajectory mechanics theory involved detailed analyses of rollover crash tests on soft soil to obtain both measured and reconstructed vehicle roll positions and trajectories. The process can be described as follows:

- 1) Determine center of gravity trajectories from videotape and film of rollover events to identify potentially airborne segments.
- 2) Compare vehicle trajectories to parabolic model to identify airborne or *effectively* airborne segments.
- 3) Reconstruct ground contact roll positions from physical evidence without reference to the videotape or film record of the rollover events.
- 4) Compute speeds at reconstructed roll positions using a uniform drag factor, from which the airborne path of the center of gravity is modeled using trajectory mechanics.
- 5) Compare elevation changes achieved during a rollover event with that computed from trajectory mechanics.

ROLLOVER CRASHES UTILIZED IN STUDY

A high speed dolly rollover test [6,7,8,9] of a Chevrolet Blazer, and a real world high-speed rollover crash [5] of a Ford Explorer videotaped by a law enforcement vehicle were analyzed to evaluate the application of the model. The rollover test and crash are summarized in Table 1, and are briefly described below.

Table 1. General vehicle and test information for the two rollover events studied.

	Rollover Crash	
	Dolly Test	Real-World
Crash Date	1/10/1995	5/22/2005
Exponent Test No.	PH04668	
Vehicle Year	1989	2003
Vehicle Make	Chevrolet	Ford
Vehicle Model	S-10 Blazer	Explorer
Packaging	2-dr 4X4	2-dr 4X4
Drive train	4.3L V-6 Auto	4.0L V-6 Auto
Test Weight [N]	18073 (4063 lb _f)	18398 (4136 lb _f)
Distribution [F/R] %	52/48	53/47
CG Height [m] †	0.649 (25.56 in)	0.681 (26.8 in)
Dolly/Trip Speed [kph]	89 (55.3 mph)	86.9 (54.0 mph)

† CG Height data was obtained from inertial parameters measured by the NHTSA [10]

DOLLY ROLLOVER TEST

The test on soft soil [6] was documented with high-speed video/film coverage from three onboard cameras, five ground-based cameras aimed perpendicular to the roll path, one ground-based camera aimed along the roll path, two panning high-speed film cameras, and two panning real time video cameras. Stationary targets along the path aided in resolving the rollover distance as a function of time. Though the entire event was filmed, the final nearly 1-3/4 roll revolution occurred beyond fixed, high-speed camera coverage at a speed of approximately 17 mph. The test vehicle was not instrumented.

The study portion of the event documented by the fixed high-speed cameras (nearly 4 sec., or about 80% of the sequence) comprised a continuous record with discrete frames every 0.002 sec. which enabled determination of vehicle speed, roll angle, elevation and distance traveled. The camera locations with respect to the roll path were well documented, and were modeled in MAYA® to obtain horizontal and vertical position of the vehicle, calibrated with markers placed along the roll path. The temporal record of vehicle position was obtained by superposition of a wire frame model of the test vehicle on the vehicle image in individual video or film frames, shown in Appendix B, that closely represents the film record. The wire frame model with CG [10] was aligned with the vehicle image on the film by viewing the film frame through a virtual camera lens

in MAYA® to simulate the actual lens used. Since the process is manual, no quantitative assessment of uncertainty of the alignment could be determined.

The speed record was obtained by numerical differentiation of the position data, which introduced a high frequency, low amplitude fluctuating component. The speed data were filtered, by means of a simple 36-point moving average filter, and matched to the known initial condition to obtain the fundamental velocity history of the CG of the vehicle.

The test vehicle achieved significant elevations during the sequence and is utilized to demonstrate the occurrence of *effectively* airborne segments in a rollover. Since the rollover evidence along the test path was not documented, an independent determination of vehicle roll positions in the test could not be performed.

REAL-WORLD ROLLOVER

The detailed documentation of physical evidence from the videotaped real-world rollover crash [5] was sufficient to independently determine likely discrete roll positions for evaluation of the trajectory model using the measured CG path during an interval of the sequence. The crash site was digitally mapped and photographed approximately six months after the accident to document ground impacts from vehicle body panels/structural features, wheels and tires, and vehicle debris including window glass. The CG elevation for one interval was determined with the technique utilized in analysis of the dolly rollover test and illustrated in Appendix B.

RESULTS OF DOLLY TEST AND REAL-WORLD ROLLOVER

The overall results of the two rollovers studied are summarized in Table 2. Figures 3 and 4 show the sequence for the two rollovers. The Chevrolet Blazer test comprised 8 roll revolutions over approximately 62 m (204 ft) from first touchdown. The locations shown in Figure 3 correspond to selected ground contacts of sufficient magnitude to likely produce residual evidence that could be observed immediately after the test. The first four templates identify the three effectively airborne segments that were studied. The vehicle was airborne more than 40% of the time. A time-resolved depiction of the rollover sequence is shown with frame captures in Appendix C. In the real-world rollover crash the Explorer completed six revolutions and came to rest on its wheels after traveling approximately 76 m (249 ft). The Explorer rollover sequence in Figure 4 is based on documentation of roll path and vehicle physical evidence, with the study segment shown as templates 6a-6b-6c.

The drag factors shown in Table 2 for both events are overall averages; instantaneous drag factors varied widely for both events. For example, the nearly 1.8 g OTG deceleration during the second roll revolution of the dolly rollover was followed by less than 0.1 g for the third roll revolution during which the vehicle was mostly airborne. For both rollovers, the segment-average drag factor (determined between selected vehicle locations for the roll sequence) during the early portions of the events exceeded commonly used average values and generally decreased with total roll angle [5,9,11]. The average drag factor for the first 80% of the roll distance in the dolly rollover test was approximately 0.64. Additional roll mechanics results for the dolly rollover test such as time and distance histories of vehicle speed, roll angle, and roll rate are included in Appendix D.

VEHICLE ELEVATION CHANGE DURING ROLLOVER

The rolling vehicles were in contact with the ground for more than half of the total event, from initial ground contact to arrival at the rest position. However, for some portions of the events covering one roll revolution or more, the vehicles were mostly airborne. The airborne phases of the dolly rollover test are indicated on the translational speed curve shown in Figure 5. Speed fluctuations in the figure are results of numerical processing of the position data. The correlation between airborne phases of the sequence and translational speed is depicted. CG elevation along the rollover path for the first three intervals in Figure 3 and Table 3 (~5-1/2 roll revolutions), which comprised approximately 80% of the total rollover distance, is shown superimposed on the roll angle axis in Figure 5. The portions of the velocity history with nearly constant average speed correspond to potential *effectively* airborne segments. Though several ground contacts occur during each segment, the CG elevation trajectories display an approximate parabolic characteristic.

Table 2. Summary of selected results for the dolly test and real world rollover.

	Rollover Crash	
	Dolly Test	Real-World
Crash Date	1/10/1995	5/22/2005
Vehicle Weight [N]	18073	18398
Dolly/Trip Speed [kph]	89 (55.3 mph)	86.9 (54 mph)
Roll Distance † [m]	62.2 (204 ft)	76 (249 ft)
Drag Factor [G]	0.50 (0.64§)	0.43*
ΔYaw †† [deg]	~20	~102
Roll Time ‡ [sec]	5.04	6.97
Ground Contact [sec]	2.9	--
Airborne Travel [sec]	2.14	--
Number of Rolls	8	6
Peak Roll Rate [deg/s]	-918	-539
Mean Roll Rate [deg/s]	-549	-303

* - Corrected for local grade variations along the roll path.
† - Roll distance for the dolly test is defined as the distance traveled by the CG along the CG path from initial touchdown to point-of-rest.
†† - The change in yaw angle is the difference between the yaw angle at launch and the at rest yaw angle. In Test 1 the yaw angle at rest was not documented, so the yaw angle was approximated based on available camera coverage.
‡ - Event time is the total length of time from the initial ground contact following launch to the point where the CG has reached its final at rest position neglecting any additional time for the vehicle to settle.
§ - This is the average deceleration over the first approximately 80% of the event (study portion) where film analysis and photogrammetry was used to provide position and orientation data.